The impact of the winery's wastewater treatment system on the winery water footprint

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ABSTRACT

In the Mediterranean region, water scarcity has already prompted concern in the wine sector due to the strong impact it has on vineyard productivity and wine quality. Water footprint is an indicator that takes account of all the water involved in the creation of a product and may help producers to identify hotspots, and reduce water consumption and the corresponding production costs. In recent years several studies have been reported on wine water footprint determination, but mostly focused on the viticulture phase or assuming no grey water footprint at the winery since it has a treatment system. In the framework of the WineWaterFootprint project a medium-size winery was monitored, with direct measurements, regarding determination of the blue and grey components of water footprint. The determined winery water footprint ranged from 9.6 to 12.7 L of water per wine bottle of 0.75 L, the wastewater produced being responsible for about 98%, which means that the grey component cannot be disregarded. The developed scenarios show that a potential reduction of 87% in winery water footprint can be obtained with almost no investment. The challenge of reducing the grey footprint is not in technology development, but rather in the proper maintenance and monitoring of treatment systems.

Key words | sustainable wine production, water efficiency, water footprint

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INTRODUCTION

In the Mediterranean region, the increasing demand for water and the pollution of freshwater resources, driven by urbanization, agriculture intensification and climate change, are major concern issues. The already observed higher temperatures and precipitation variability are of concern to the wine sector, due to their impact on vineyard productivity and wine quality (Paulo *et al.* 2012; Costa *et al.* 2016). The adoption of the best available techniques, aiming at sustainable production, and therefore reducing the impact on natural resources, is a goal of the wine industry, once the reduction of wineries' water consumption can contribute to reduce both natural resource dependence and production costs. The water footprint (WFP) indicator can help producers to better understand their water consumption profile, to identify hotspots, to compare their performance with other producers and to reduce water expenditure.

The WFP concept was firstly introduced by Allan (1997) as virtual water and then further developed by Hoekstra & Hung (2002). The WFP indicator was born from the idea of considering water use along the supply chain and is a multidimensional indicator, considering water consumed by source and polluted volumes by type of pollution (Hoekstra *et al.* 2011). Although WFP is normally presented as an aggregate number, taking account of all the water involved in the production of a unit of a product, it includes three components: green, blue and grey water footprints. Green WFP refers to precipitation water that is stored temporarily in the soil or remains in soil or plant surfaces and that, eventually, evaporates or is consumed by plants; blue WFP corresponds to consumption of surface or groundwater resources within the process, through evaporation, incorporation into the product, or water that returns to a different water body or that does not return to the water body in the same period (Hoekstra *et al.* 2011); grey WFP indicates the amount of freshwater needed to assimilate pollutants, so that, based on natural concentrations, a given water quality standard is achieved (Hoekstra *et al.* 2011; Mekonnen & Hoekstra 2011). The first reported work on the WFP assessment of a product was the WFP of cotton in 2006 (Chapagain *et al.* 2006) while the first WFP assessment for wine was reported by Mekonnen in 2010 (Mekonnen & Hoekstra 2010).

The assessment of wine WFP from viticulture to the winemaking industry has been addressed by several authors in several regions and at different levels of temporal resolution (Ene *et al.* 2013; Herath *et al.* 2013; Lamastra *et al.* 2014; Quinteiro *et al.* 2014; Bonamente *et al.* 2016; Iannone *et al.* 2016; Rinaldi *et al.* 2016; Martins *et al.* 2018; Villanueva-Rey *et al.* 2018). However, some studies have been focused on the viticulture phase of the wine WFP and thus have not considered the grey WFP of the winemaking process (Lamastra *et al.* 2014; Bonamente *et al.* 2016; Villanueva-Rey *et al.* 2018; Borsato *et al.* 2019). Other studies assumed that the wastewater produced at the winery is treated to a level that does not present grey WFP or that the WFP corresponds to no more than the volume of wastewater generated (Ene *et al.* 2013; Herath *et al.* 2013; Bonamente *et al.* 2015). A recent study focused on the assessment of grey WFP of winery wastewater was performed with direct data but considered a co-treatment system with municipal wastewater, which is a particular case (Johnson & Mehrvar 2019). The effective treatment efficiency and the quality of the treated wastewater was, as far as we know, never evaluated in the determination of grey water footprint and is therefore an improvement to the current state of the art. The direct monitoring of case studies and the impact of the treatment system efficiency on the overall winery WFP should therefore be evaluated, since most reported studies did not use original and site-specific data (Ferrara & De Feo 2018).

Other studies conducted at wineries only considered the water consumption or presented the characterizations of wastewater flows, without determining the winery WFP (Giacobbo *et al.* 2013; Oliveira & Duarte 2016). Previous studies on winery wastewater flows reported a high pollution load, especially during vintage and racking periods (Oliveira *et al.* 2009). In addition, these wastewaters are usually characterized by low pH, high salinity and nutrient levels which indicate that they have a potential impact in the environment (Mosse *et al.* 2011), if discharged or disposed without appropriate treatment. Also, the large volumes of water consumed, and wastewater produced, throughout winemaking operations indicate that water recycling should be a priority. Consequently, the measures employed to minimize the environmental impacts of the winery industry, through technologies adapted to environmental constraints, with the aim of reducing both water consumption and waste and recovering by-products are crucial as specified in ISO 14001 (ISO 14001:2015). An optimized treatment system and its continuous monitoring may allow both the reduction of the overall winery WFP and the reuse of the treated wastewater, with environmental benefits.

This work aimed to determine the winery WFP of a Portuguese medium-size winery located in the Tagus wine region, to evaluate the effective efficiency of the wastewater treatment system and to determine its overall impact on the winery WFP. A medium-size winery was selected, aiming at a higher representativeness of the study, since 75% of Portuguese wine is produced in medium and large wineries (Oliveira *et al.* 2019).

METHODS

The objective of the study was to determine the WFP of a bottle of wine produced in a medium-size winery, located in the south of Portugal, Tagus wine region, with a production capacity of 750,000 L. The impact of wastewater treatment efficiency on WFP was also addressed through the design of different scenarios.

The study was carried out in 2017 and 2018 at level C of spatio-temporal resolution, which implies geographically and temporally explicit data accounting, based on the collection and treatment of primary and secondary data on water flows and quality, according to Hoekstra *et al.* (2011). The defined system boundary thus included the direct water use of all the processes in the winery and bottling, not taking into account the water use related to grape growing, transportation, machinery, etc (Figure 1).

Wine production involves different operations that require water. Given the simultaneous nature of the operations, it is not always possible to segregate all the phases of the process, so the operations were grouped into vintage, post-vintage and bottling. The water used at the different winery activities was continuously monitored through a water meter installed at the winery, developed by Eddy-Home Company. This solution collects all the data concerning water consumption in real time, but also integrates functionalities that allow data analysis. The functional unit (FU) selected for this study was 0.75 L of the commonly used wine bottle.

Winery water footprint

The WFP of a product is comprised of the sum of the WFP of the different processes involved in its production. Regarding the winemaking phase of wine production, the WFP of the product is determined by the sum of the WFP of the different processes divided by the overall production,

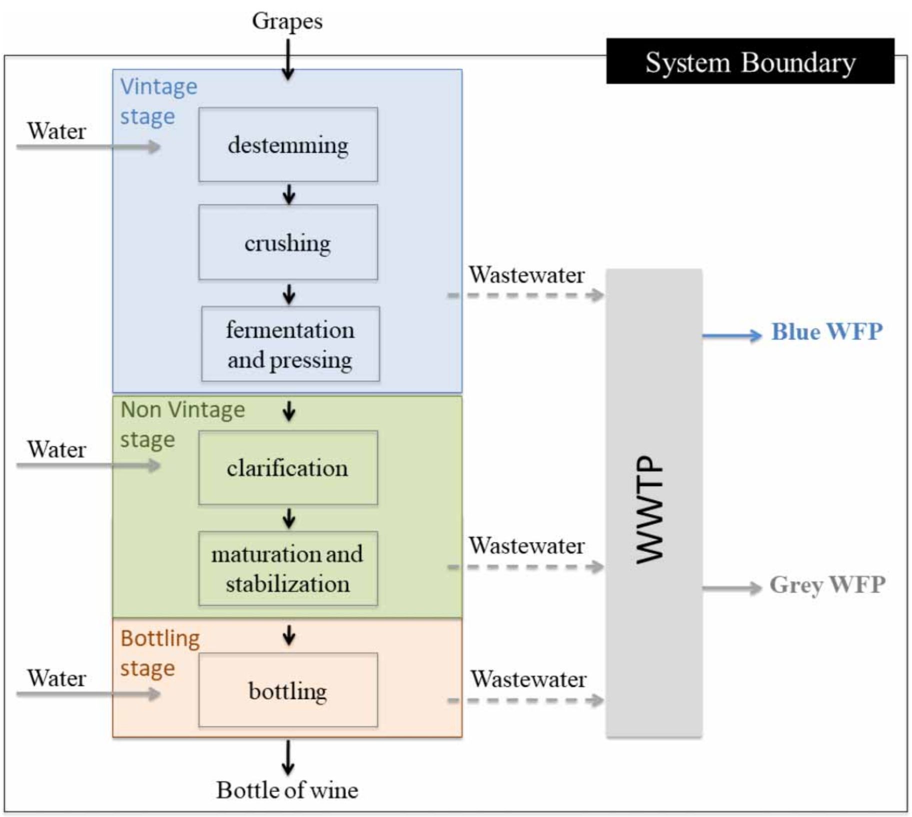

Figure 1 | Diagram describing the winemaking process and definition of the system boundary used in water footprint determination. Adapted from Borsato *et al.* (2019).

according to Equation (1):

$$WF_{\text{prod}}\,[p] = \frac{\sum_{s=1}^{k} WF_{\text{proc}}\,[s]}{P\,[p]}\ [\text{volume/volume}] \qquad (1)$$

where WF_{proc} is reported in volumes of water (L/time) and P is the corresponding wine production (L/time).

For each wine production process, it is necessary to determine the different WFP components involved which, at the winery, correspond only to blue and grey WFP.

The blue WFP represents consumptive use of water and is determined by the sum of water evaporation, water incorporation and return flow, according to Equation (2):

$$WF_{\text{proc,blue}} = Blue_{\text{WaterEvaporation}} + Blue_{\text{WaterIncorporation}} + Lost_{\text{Returnflow}}\ [\text{volume/time}] \qquad (2)$$

where $Blue_{\text{WaterEvaporation}}$ represents the volume of evaporated water (L/month), $Blue_{\text{WaterIncorporation}}$ the volume of incorporated water (L/month) and $Lost_{\text{Returnflow}}$ the volume of water (L/month) that does not return to the water body in the same cycle.

Regarding winery activities, the blue water footprint is related only to the evaporation that occurs in winery activities once there is no incorporation and it returns to the water body in the same period. This is why the blue water footprint does not always correspond to the winery water use, usually reported. In this study the water evaporation from the wastewater treatment plant was determined according to the Penman equation (Penman 1948) while the evaporation from the winery washes was not considered due to its predicted low overall impact and difficult determination.

Regarding the grey WFP, the wastewater produced was monitored in a dedicated wastewater treatment plant, consisting of an air micro-bubble bioreactor (AMBB) with 350 m^3 of capacity, along two complete cycles of wine production. Composite samples of the winery wastewater, representative of each stage of the process, were taken and maintained at 4 °C. During vintage the sampling was carried out weekly and during non-vintage and bottling periods the sampling was carried out twice a month. The pH, chemical oxygen demand (COD) and biochemical oxygen demand (BOD) were monitored, following OIV guidelines for sustainable viticulture (OIV 2011). For complementary characterization, in accordance with local regulation, electrical conductivity, total suspended solids (TSS), total nitrogen, phenolic compounds and total phosphorus were monitored, according to Standard Methods (APHA 2006). The physical–chemical analysis of the treated wastewater allows the determination of the limiting parameter used in grey WFP calculation (Table 1).

The winery wastewater flow was evaluated from water use once there is no consumptive use of water at the winery. Results were compared with the water quality standards for water body discharge. The grey WFP was determined monthly by the total amount of water that is necessary to assimilate the load of pollutants based on natural background concentrations in the environment and water quality standards (DL 236/98), according to Equation (3) (Franke et al. 2013):

$$WF_{\text{proc,grey}} = \frac{L}{C_{\max} - C_{\text{nat}}}\ [\text{volume/time}] \qquad (3)$$

where L corresponds to the pollutant load (g/month) and $C_{\max}$ and C_{nat} to the maximum and natural allowed concentration for the considered pollutant (g/L).

Efficiency of wastewater treatment plant

In order to evaluate the efficiency of the wastewater treatment plant, both the inlet and outlet wastewater were monitored. The parameters followed were pH, electrical conductivity, total suspended solids, chemical oxygen demand, biochemical oxygen demand, total nitrogen, phenolic compounds, total phosphorus and microbiology, according to Standard Methods (APHA 2006). For the determination of the treatment efficiency, regarding the removal of contaminants, the limiting parameter used in the calculation of the grey water footprint was considered. Treatment efficiency

Table 1 | Standard Methods for the examination of wastewater and water quality standards (APHA 2006; DL 236/98)

Parameter	Standard Methods code	Water Quality Standard for water body discharge Portugal DL 236/98
pH (Sorensen)	4500-H^+ B	6.0–9.0
Conductivity (μS cm^{-1})	2510 B	–
COD (mg O_2 L^{-1})	5220 D	150
BOD (mg O_2 L^{-1})	5210 D	40
TSS (mg L^{-1})	2510 B	60
Phenolic compounds (mg L^{-1})	Folin index	–
Total nitrogen (mg L^{-1})	4500-N_{org} B	15
Total phosphorus (mg L^{-1})	4500-P E	10

was determined according to Equation (4):

$$\text{Treatment efficiency} = \frac{L_i - L_f}{L_i} \times 100\,[\text{percentage}] \quad (4)$$

where L_i corresponds to the initial load of the selected pollutant and L_f to the final load of the pollutant.

To assess the impact of the wastewater treatment efficiency in the WFP, two scenarios were considered: Scenario I considering 20% improvements and Scenario II considering the optimum treatment efficiency for the AMBB, reported by Oliveira et al. (2009).

RESULTS AND DISCUSSION

Winery water footprint

For the determination of the blue WFP component, the amount of water evaporated per month during the two years of monitoring was evaluated. From the analysis of Figure 2 it is possible to verify that the two years under monitoring had different atmospheric conditions, with emphasis on a heat wave during August of the second year, from which originated an abnormal evaporation. This heatwave had a duration of six days and during this exceptional episode there was even observed the highest mean value of maximum air temperature since 1931, confirming its exceptional character (IPMA 2018). This extreme climatic episode had repercussions both for grape production and evaporation with a decrease of around 30% in wine production and an increase of about 60% in evaporation, when comparing August 2017 with August 2018. Besides the different atmospheric conditions of the two years under monitoring, the evaporation of the second year was only 3% lower in comparison with the first year of monitoring. The decrease in production generated a proportional increase in water footprint, concerning blue WFP calculation, where evaporated water is divided by the amount of wine produced.

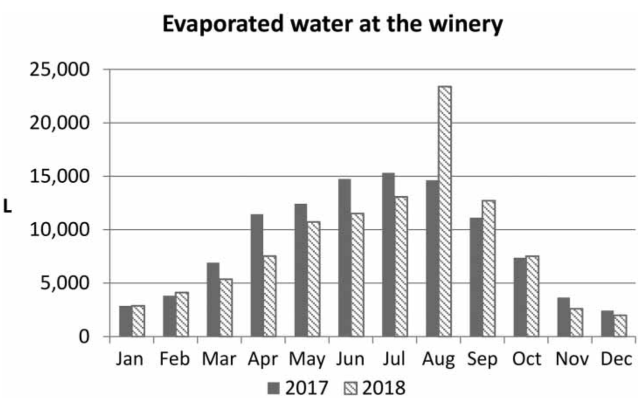

Figure 2 | Monthly evaporation occurring at the winery for both monitored years.

Regarding the blue WFP (Table 2), it is possible to verify that besides the slightly lower evaporation of the second year of monitoring, an increase can be observed in the blue WFP of around 33%. As observed, the higher blue WFP is due to the decrease in wine production and has therefore no impact on the amount of evaporated water. The low value of blue WFP, in both years, accords with other reported results for the Mediterranean region that also verified an almost insignificant value of blue WFP component at the winery, when compared with the overall winery WFP (Quinteiro et al. 2014; Bonamente et al. 2016).

Regarding grey WFP calculation, the limiting pollutant was firstly determined, based on the monitored parameters (Table 1). It was found that chemical oxygen demand was the parameter that presented the greatest difference to C_{max}, meaning the one that needs the highest dilution rate. The average physical and chemical characterization of the treated wastewater is shown for both years (Table 3). From the results it is possible to observe that the average pollutant load of the treated wastewater was lower in the second year of monitoring, which accords with the verified production loss and consequent reduction of pollutant load of the generated wastewater.

Figure 3 shows the amount of effluent discharged into the water body and corresponding grey WFP per month and year. It is possible to observe that there is little or no discharge during the months from May to November, the period in which the treated effluent was reused in vineyard irrigation. If the treated effluent does not meet water quality standards, due to an inadequate level of treatment, or an incorrect dilution is used during irrigation reuse, it may contribute to a higher grey WFP of the vineyard, which is outside the scope of this study and was not therefore evaluated.

The calculation of the monthly grey WFP includes the amount of discharged, treated effluent and the corresponding COD concentration to determine the COD load. The

Table 2 | Water evaporation, wine production and the corresponding blue WFP for two years of monitoring

	Evaporation (L)	Wine production (L)	Blue WFP (L_{water}/0.75 L_{wine})
2017	106,793	723,945	0.15
2018	103,509	508,695	0.20

Table 3 | Average physical and chemical characterization of the treated wastewater for both years of monitoring

Parameter		2017 Mean	2017 n	2018 Mean	2018 n
pH	(Sorensen)	5.5	42	7.3	32
Electrical conductivity	(μS/cm)	2,091	42	1,742	32
Total suspended solids	(mg/L)	1,442	20	462	17
Chemical oxygen demand	(mg/L)	3,819	20	1,602	17
Biochemical oxygen demand	(mg/L)	1,137	20	1,302	17
Total nitrogen	(mg/L)	35	20	17	17
Total phosphorus	(mg/L)	77	20	35	17

n = number of sample results available.

COD concentration of the discharged effluent ranged from 79 to 4,358 mg/L in the first year of monitoring, and from 82 to 4,024 mg/L in the second year of monitoring. The higher COD values were associated with the vintage period, which is corroborated by other studies that also identified a higher pollutant load during vintage (Petruccioli *et al.* 2002; Oliveira *et al.* 2009; Johnson & Mehrvar 2019). The total amount of treated effluent and the corresponding grey WFP are shown in Table 4. The results revealed that the amount of effluent was similar in both years, which means that despite the reduction in processed grape there was no corresponding reduction in the water use. This could be related to the fact that the equipment is optimized to process a larger amount of grape. Regarding the average concentration of the COD (Table 3) and although the measured range was similar in both years, a lower pollutant load was observed in the second year of monitoring (Table 4), which is explained by the similar amount of

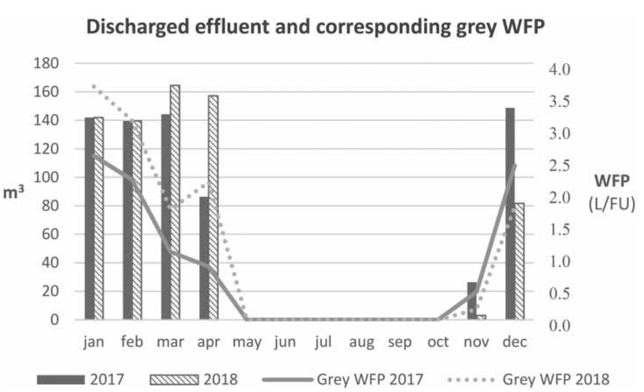

Figure 3 | Monthly amount of treated effluent discharged at the natural water body and corresponding grey WFP, during the two years of monitoring.

Table 4 | Discharged effluent, COD load and corresponding grey WFP for two years of monitoring

Year	Discharged effluent (L)	COD load (kg)	Grey WFP (L_{water}/0.75 L_{wine})
2017	687,202	1,028	9.47
2018	687,962	957	12.54

effluent and the reduction of processed grape. Overall, the grey WFP increase, by around 32%, from the first to the second monitoring year is explained by the decrease in production and not because of a greater impact on the natural resources. This result is in line with the results of the blue water footprint, which shows that the increase of the WFP could be mostly explained by the decrease in production.

Overall, the winery WFP determined in this study ranged from 9.6 L_{water}/0.75 L_{wine} in the first year of monitoring to 12.7 L_{water}/0.75 L_{wine} in the second year. These results are lower than other reported results due to the effluent reuse in irrigation. An integrated approach with vineyard WFP calculation should obtain the closest results to the ones reported by Lamastra *et al.* (2014) and de Pina *et al.* (2011). The grey WFP is, as expected, the most important contributor to winery WFP, representing more than 98% of the winery WFP, which is in line with other reported results (de Pina *et al.* 2011). Other authors that focused their work on winery grey WFP also estimated a significant grey WFP due to winery wastewater (Johnson & Mehrvar 2019) instead of the results reported by Ene *et al.* (2013), Herath *et al.* (2013) and Bonamente *et al.* (2015). An adequate and efficient treatment system is therefore essential to sustainable wine production.

Efficiency of wastewater treatment plant

Considering the limiting pollutant, the treatment efficiency of the wastewater treatment system was determined for both years of monitoring. The treatment efficiency observed in the first year of monitoring was then compared with the reported optimum efficiency for the existing treatment system. Then two improvement scenarios were designed: the first considering a 20% improvement in the average efficiency (scenario I) and the second considering an optimum treatment efficiency for the AMBB, reported as 93% (scenario II) (Oliveira *et al.* 2009).

The average wastewater treatment efficiency observed in the first year of monitoring was 45%, which corresponds to a grey WFP of 9.47 L_{water}/0.75 L_{wine}, while in the second year it was 47% with a corresponding grey WFP of

12.54 L_{water}/0.75 L_{wine}. The observed treatment efficiency in the two years was about half the optimum treatment efficiency, so there is room for improvement.

The created scenarios allow us to predict the impact that improvements in the wastewater treatment system will have on grey WFP (Table 5). From the analysis of the results it is possible to verify that the improvement scenarios generated a great potential reduction of grey WFP with a slight increase of treatment cost.

When evaluating the impact of the improvement scenarios on the overall winery WFP it is expected that a reduction in winery WFP will be observed of the same magnitude as of grey WFP reduction, once grey WFP is the biggest contributor to winery WFP, representing more than 98% of winery WFP. From the analysis of Figure 4 it is possible to verify that the increased treatment efficiency of scenarios I and II originated a positive response in grey WFP reduction, and consequently in winery WFP, with high environmental benefits. In fact, the increase of 20% in the treatment efficiency of scenario I led to a reduction of almost the same percentage in the winery WFP. When considering a further improvement of treatment efficiency, corresponding to the reported optimum performance, the potential reduction of approximately 87% in winery WFP reinforces the importance of a continuously monitored and well-kept treatment system.

Most of the authors that have reported wine WFP focused only on the viticulture stage of the winemaking process (Lamastra *et al.* 2014; Bonamente *et al.* 2016), and assumed that the grey WFP is zero or almost nonexistent (Ene *et al.* 2013; Herath *et al.* 2013; Bonamente *et al.* 2015) or simply used reported values in grey WFP calculation (de Pina *et al.* 2011; Johnson & Mehrvar 2019). This type of analysis, based on case studies and direct measurement, is important once the treatment systems are normally considered as being in perfect working condition and with optimum performance, which was not verified in this case study. In fact, if this study had considered that the treatment system was working at its optimum efficiency then the reported winery WFP would be around 1.36 L_{water}/0.75 L_{wine} instead of the observed 9.62–12.47 L_{water}/0.75 L_{wine}, with an underestimation of almost ten times.

Table 5 | Different scenarios of treatment efficiency, aeration time (t_{AR}) and their impact on grey WFP and treatment cost

Scenario	Average treatment efficiency	t_{AR} (h/day)	Grey WFP (L_{water}/0.75 L_{wine})	Additional cost (€/0.75 L_{wine})
Real	45%	6	9.47	–
I	65%	8	7.58	0.002
II	93%	12	1.21	0.005

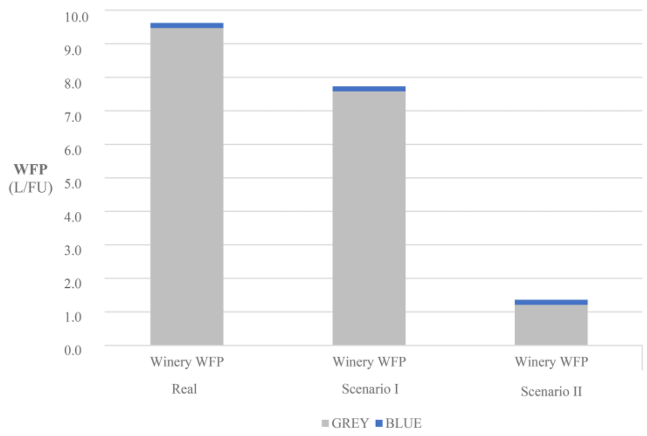

Figure 4 | Comparison of the winery WFP with the developed improvement scenarios.

The developed scenarios concerning the improvement hypotheses can be implemented by the winery with low investment. Scenario I may be reached only by the modification of the aeration control system, with higher aeration during high load production phases and lower aeration in the remaining periods. Scenario II considers the optimum treatment scenario with all the equipment at its peak performance and requiring the substitution of existing worn-out equipment.

CONCLUSIONS

WFP is a recent, but important, indicator regarding environmental performance since it can help both producers to better identify hotspots or inefficiencies, and consumers to identify products that have been obtained with a lower environmental impact.

The determination of the wine water footprint has been already reported, but mainly focused on the viticulture phase or considering the absence of the grey water footprint in the winery, since it has a treatment system. The aim of this study was to assess the effective efficiency of the wastewater treatment system and to determine its overall impact on the winery WFP.

The grey WFP is the most relevant component regarding winery WFP with more than 98% of the total WFP. The developed scenarios predicted the grey WFP reduction, based on wastewater treatment system improvements. It was found that a 20% increase in treatment efficiency allowed for a WFP reduction of the same magnitude. In addition, the study revealed the possibility of an 87% reduction in the winery WFP, with an increase in fixed costs of only 0.005€/bottle. A suitable treatment system, with adequate monitoring and maintenance procedures, is therefore essential. The definition of different operational setpoints, based on production phase, enables industries to save energy and improve water management in low-load production phases with corresponding environmental and economic benefits.

This study showed that, although many authors disregard the grey component of the winery WFP, this sub-indicator has a relevance that cannot be overlooked.

The water footprint indicator varies with geographic position, due to the impact of meteorological conditions, and although the chosen case study may be considered representative of the Tagus wine region, future work should be conducted considering the existence of the grey WFP component at the winery.

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